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# SHORT COMMUNICATION

# TIME-AVERAGED FLOW STRUCTURE IN THE CENTRAL REGION OF A STREAM CONFLUENCE: A DISCUSSION

S. N. LANE[1]*, K. F. BRADBROOK[1], K. S. RICHARDS[1], P. M. BIRON[2] AND A. G. ROY[2]
[1]*Department of Geography, University of Cambridge, Downing Place, Cambridge, CB2 3EN, UK*
[2]*Département de Géographie, Université de Montréal, CP 6128 Succ. Centre-Ville, Montréal, Québec, H3C 3J7, Canada*

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## ABSTRACT

This paper is a discussion of Rhoads and Kenworthy (1998) 'Time-averaged flow structure in the central region of a stream confluence' *Earth Surface Processes and Landforms*, **23**, 171–191, that focuses upon the methods used to identify secondary circulation in river channel confluences. It argues that the Rozovskii method that Rhoads and Kenworthy use to rotate their field data to allow identification of secondary circulation cells is flawed, and can result in misleading conclusions about the nature of flow processes in confluences. It recommends that there is a re-emphasis upon helical as opposed to secondary circulation, and that recent developments in both field monitoring and numerical modelling may help significantly in this respect. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: river confluences; secondary circulation; helical circulation; tributary junctions

## INTRODUCTION

There is no doubting the quality of the field data presented by Rhoads and Kenworthy (1998), and the care with which it has been analysed and presented. Indeed, it is the clarity of the Rhoads and Kenworthy argument that has allowed this discussion to be written. However, their paper reinforces a growing concern that we have over the extent to which current research on river channel confluences draws upon interpretative methods that are not entirely appropriate for this particular flow problem. A full exposition of the arguments presented in this discussion is provided in Lane *et al.* (in press), but here we focus specifically on the analytical methods used by Rhoads and Kenworthy.

## THE MEANDERING LEGACY

Our main concern is with the manner in which secondary circulation is defined, using a method necessitated by the type of point-sampled data used to characterize the flow. This analytical method is based upon a velocity rotation scheme originally developed for river meanders (e.g. Rozovskii, 1954; Bathurst *et al.*, 1977). The scheme is necessary to separate out secondary flow from primary flow. This is particularly important where the field data are obtained by measuring a finite number of points in a finite number of cross-sections, and allows visualization of the intensity of secondary circulation in different morphological situations.

Whilst identification of secondary flow is straightforward in channels with regular boundaries and a slow rate of change of channel curvature, this is less the case where river channel boundaries are irregular, identification of the direction of primary flow is difficult, and hence separation of primary and secondary

* Correspondence to: Dr S. N. Lane, Department of Geography, University of Cambridge, Downing Place, Cambridge, CB2 3EN, UK. Email: SNLIO@cam.ac.uk
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flows is not easy. Other research has applied this same method to the identification of secondary flow in confluences (e.g. Ashmore *et al.*, 1992; Rhoads and Kenworthy, 1995; Rhoads, 1996; Rhoads and Kenworthy, 1998), where it is also difficult to identify the exact orientation of the primary flow direction. The Rozovskii method is based on identifying the direction of the depth-averaged velocity at an individual vertical, and then separating flow at every elevation in that vertical into one component parallel to the direction of the depth-averaged velocity (assumed to be the primary flow component), and a second component tangential to the direction of the depth-averaged velocity (assumed to be the secondary flow component). Rhoads and Kenworthy (1998) provide a thorough and clear explanation of this method, and how it may be applied in confluences. The purpose of this discussion is to evaluate critically application of this method to river channel confluences.

## THE INEVITABILITY OF SECONDARY CIRCULATION

Our first concern relates to the *inevitability* of secondary circulation identified using the Rozovskii definition. As Dietrich and Smith (1983, 1984) recognized for meander bends, 'secondary circulation' involves net cross-stream and downstream transfer of mass and momentum in the form of a helix, rather than as a closed circulation cell. In terms of meander research, this observation resulted in a major shift away from the Rozovskii methodology in the mid-1980s, as it forces zero net secondary discharge at each vertical even though there may be situations in meanders where secondary discharge is uni-directional *throughout* a vertical (Hey and Rainbird, 1996).

This will also be true for flow in a river confluence. The Rozovskii method will produce an apparent circulation cell or cells whenever there is flow convergence (predicting convergent secondary velocities at the water surface) or flow divergence (predicting divergent flow velocities at the water surface). Whilst some circulation almost certainly exists, the effect of a zero net discharge assumption will be to exaggerate the amount of secondary circulation that is estimated. This is illustrated when the method is applied to predictions from a numerical model of mixing in a confluence of a channel with parallel tributaries and bed discordance (Figure 1), where a circulation cell is introduced for the entire flow cross-section when the original model predictions suggest only a small circulation cell confined to the channel sidewall. Similarly, whilst Biron *et al.* (1993, 1996) do not identify twin back-to-back, surface-convergent circulation cells in their study of a confluence with discordant beds, application of the Rozovskii method to the predictions from a numerical model of this confluence does indeed produce such cells. This may suggest that differences in the opinions of researchers over the importance of various controls upon secondary circulation may be as much to do with differences in the data analysis method as to do with real differences in the measured flow fields.

Rhoads and Kenworthy argue that the pattern of weak secondary circulation that they identify may be related to curvature of flow streamlines. We agree that this is likely, but would caution against reaching this conclusion on the basis of data transformed by the Rozovskii method. Following from its definition, the depth-averaged flow direction will be identical to the direction of the depth-averaged streamline curvature (the depth-averaged streamlines are those across which there is no net discharge). The strength of the secondary discharge will also be a function of the direction of the depth-averaged flow direction. Thus, there is an element of circularity in relating patterns of secondary circulation identified using the Rozovskii method to streamline curvature. We would argue that what confluence research (and perhaps meander research) needs is a more explicit recognition of generating processes. What creates strongly three-dimensional flow fields is the interaction of pressure gradients within the flow. Progress in understanding what creates three-dimensional flow structures comes more from understanding how three-dimensional morphology (i.e. planform curvature *and* bed elevation change) creates these pressure gradients under different combinations of tributary discharge (e.g. Bradbrook *et al.*, 1998).

## CROSS-STREAM VARIATION IN THE SECONDARY CIRCULATION PLANE

The second problem with the Rozovskii approach is well recognized by Rhoads and Kenworthy: it generates apparent cross-stream variability in the direction of the depth-averaged flow vector, and hence in the plane

 

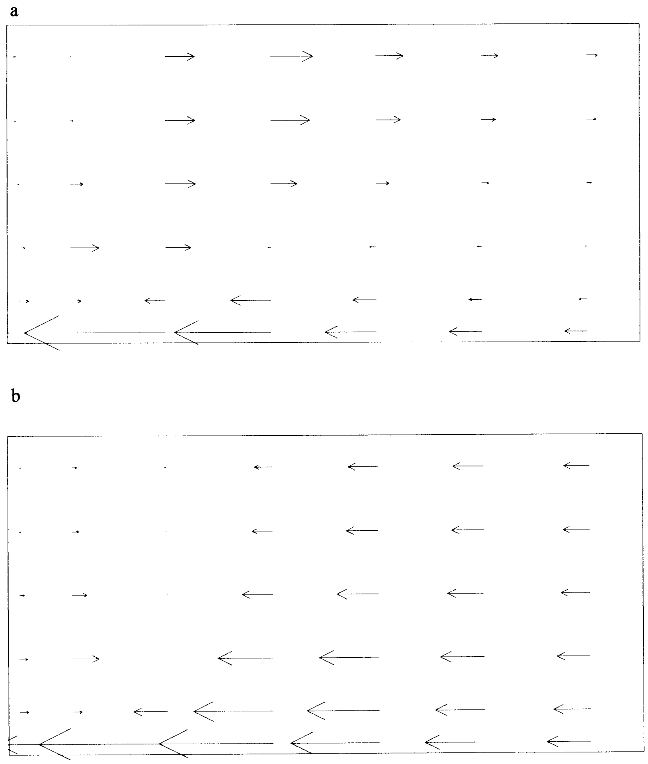


Figure 1. Application of the Rozovskii method to the parallel laboratory confluence. This plot shows sampled secondary velocities estimated by this method (a) and the raw output cross-stream velocities (b), with modelled $v_z$ for reference

within which the secondary circulation is identified. As they note, this is particularly problematic if, as one would expect, the direction of the depth-averaged flow changes as a function of stage. It is necessary to have a fixed cross-section and to map the primary and secondary flow components back onto this cross-section. Rhoads and Kenworthy therefore focus upon the cross-stream component of secondary circulation ($v_{sy}$), by taking the observed values of secondary velocity estimated by the Rozovskii method ($v_s$), and multiplying them by the cosine of the depth-averaged flow direction. Two problems arise here. First, the magnitude of $v_{sy}$ which is now identified is dependent upon the definition of $x$ and $y$, which is presumably meant to correspond to the downstream and cross-stream directions, even though one of the prime aims of the Rozovskii method was objective identification of the magnitude of secondary circulation without the subjectivity that identification of cross-section orientation implies. Second, Rhoads and Kenworthy offer no consideration of $v_{sx}$, which when there is strong variability in the depth-averaged flow direction across a cross-section, may be quite large.

## WHEN DO THE TRIBUTARIES BECOME A SINGLE CHANNEL?

The third issue is that these difficulties of section orientation are amplified by the special nature of confluences, where the primary flow is created by the junction of two tributary flows, separated by a free shear layer. A key question arises: when do the two primary flows of each tributary become a single primary flow in the main channel? The Rozovskii method fails to recognize the presence of a shear layer between the two confluent flows, and hence two primary flow directions each of which is being progressively aligned to become parallel to the other with increasing downstream distance through the confluence. This shear layer may exist for a significant distance downstream; indeed, over several channel widths before the two flows become fully mixed (e.g. Gaudet and Roy, 1994)

Aside from the hydrodynamic importance of the shear layer, there might be some case for different definitions of section orientation either side of the shear layer. More specifically, the difference in primary flow directions results in a variation in the orientation of the cross-section alignment which amplifies the strength of secondary circulation identified using the Rozovskii definition, and hence the importance of the Rhoads and Kenworthy (1998) correction in determining the downstream and cross-stream components of both primary and secondary velocity.

## THE PROBLEM OF INFERRING VERTICAL VELOCITIES AND FLOW PATHS

Fourthly, it is important to ask why flow field rotation is necessary. The long-established reason is the effect that downwelling and upwelling can have upon the core of maximum velocity and hence the magnitude and distribution of bed shear stress. In addition, it is recognized that the three-dimensional structure of the flow field in the downstream direction may be important as this can significantly affect the routing of sediment and hence zones of erosion and deposition. Having identified some form of cross-stream flow field, vertical velocities are inferred by assuming that there is no flow acceleration in the downstream direction (even if this may contradict the essence of the spiralling motion that helical flow implies, and which is well documented in river channel confluences), and where there is convergence of components of secondary circulation, the flow must either downwell or upwell. As the Rozovskii method tends to result in circulation cells that occupy a large proportion of the channel cross-section, the zones of inferred downwelling tend to be in the right place, but have the wrong extent and intensity. Because acceleration effects are not considered, magnitudes of upwelling and downwelling are over-estimated. This will be exacerbated when the estimation of downwelling or upwelling magnitude is based upon $v_{sy}$ estimates which are an incomplete representation of $v_s$ (see above). Thus, even qualitative inference asimilar to that of Rhoads and Kenworthy (1998, e.g. figures 9 to 11) will be difficult given the way in which the Rozovskii method changes the spatial extent of the secondary circulation cell (e.g. figure 1 in Lane *et al.*, in press).

Numerical model predictions can be used to investigate this problem by comparing vertical velocities suggested from patterns of $v_{sy}$ estimated using the Rozovskii method with those predicted by the model, for a numerical model of flow structure in the field confluence reported by Rhoads and Kenworthy. For this purpose, the analysis has inferred vertical velocities by: (i) determining the centre of the circulation cell suggested by patterns of $v_{sy}$ in the simulation; (ii) inspecting $v_{sy}$ values to determine net changes in cross-stream velocity between adjacent verticals, and from the sign of this change, to determine the magnitude of inferred vertical velocities; and (iii) assigning a direction to these velocities according to the position of the point velocity with respect to the circulation cell centre and the sense of rotation suggested by the circulation cell itself. The results are shown in Figure 2. This illustrates a severe over-estimation of both upwelling and downwelling motion, as well as an inaccurate portrayal of the locations of zones of upwelling and downwelling. In particular, the method predicts large amounts of upwelling, when the model actually suggests small-magnitude downwelling. Figure 2 also plots modelled vertical velocities against inferred velocities with a different cross-section rotation method. This uses modelled vertical velocities to estimate the position of the free shear layer, and then applies a Dietrich and Smith (1983) rotation on each side of this layer. The result is a much better qualitative representation of vertical velocity patterns, even if the quantitative agreement is still poor.

The poor representation of vertical velocities that arises from the Rozovskii method is perhaps inevitable: definition of the elevation of the depth-averaged velocity in the vertical always results in secondary flow in one direction in one half of the vertical and in the opposite direction in the other half. Just as Hey and Rainbird (1996) note that the Rozovskii method does not allow for the possibility of unidirectional flow within a cross-section of a meander, vertical velocities inferred using this method in a confluence do not allow for unidirectional upwelling or downwelling within a single confluence cross-section.

The assumption that makes inference of vertical velocities possible is that there are coherent circulation cells within individual cross-sections within a confluence. At any confluence with a scour-hole or bed discordance, as seems to be the case in most confluences (Kennedy 1984) and is clearly the case in the Kaskaskia-Copper Slough (Rhoads and Kenworthy, 1998. figure 4), there should be net downwelling to allow

 

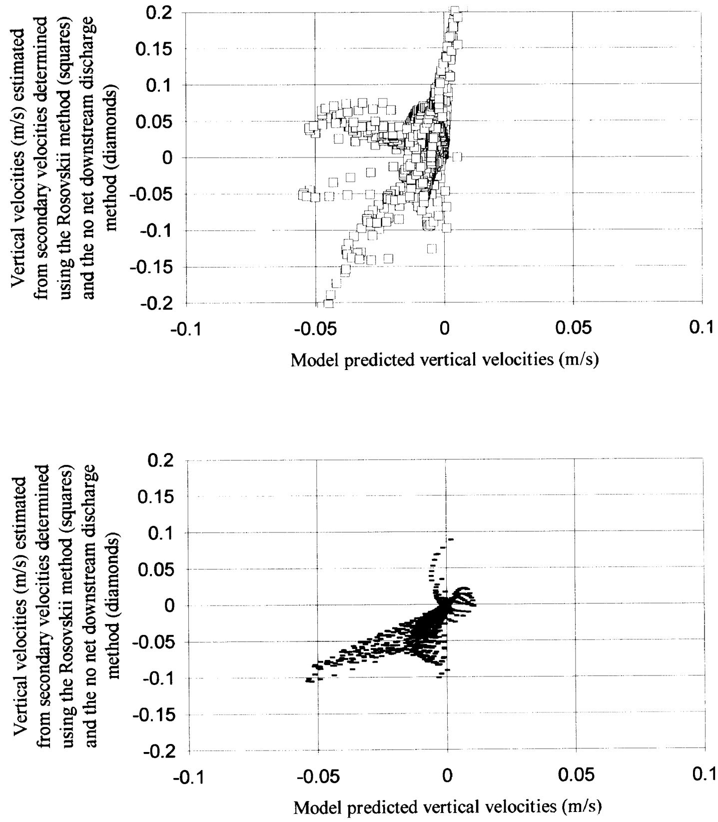


Figure 2. (a) Scatter plot of vertical velocities inferred from $v_s$ for the Rozovskii method (squares). (b) The results of applying a Dietrich and Smith (1983) type method based upon mass continuity, but where the rotation is applied to single planes either side of the shear layer (bars)

mass to fill the progressive increase in channel capacity. This should result in the majority of the vertical velocities being negative and does not require the scour-hole slope to be sufficiently steep for there to be flow separation. Thus, the coherence of the helical cell at any one cross-section (but not the helical circulation through a number of cross-sections) should be minimal. It may be the case that there has been too much concern with identification of coherent secondary circulation cells, at the expense of the helical paths followed by particles of fluid in the downstream direction, which will inevitably result when methods are used which misrepresent the real nature of vertical velocities. It follows that as the circulation patterns identified by the Rozovskii method will bear little resemblance to the actual flow field in which particles travel, it does not really help in understanding the sediment routing question either.

## INTERMITTENCE, AVERAGING AND THE EMERGENCE OF COHERENCE

Finally, there remains a fundamental difficulty with field measurement of confluence flow structure, and this reflects the unsteady nature of the three-dimensional flow field. As Rhoads and Kenworthy recognize, it is possible that the mean flow field identified from averaging a time-series of instantaneous velocity components measured at a series of points is actually a manifestation of a periodic eddy-shedding process. Rhoads and Kenworthy argue that this is unlikely to be occurring in their study owing to a lack of flow separation at the bed. However, bed separation is not the only process which can lead to flow field instabilities which could produce time-averaged manifestations. The key process that will produce a flow field instability is a very strong pressure gradient, where mass can be drawn from areas of high pressure to areas of low pressure until the pressure gradient is instantaneously reversed and hence the flow field is reversed. It is then

that an eddy is shed. Thus, bed discordance, without flow separation from the bed, may generate periodic flow instability, if it has sufficient effect upon bed pressure gradients. Whether or not bed discordance has this effect will depend upon not only bed morphology but velocity and momentum ratios, each of which can result in very different bed pressure gradients (Bradbrook *et al.* 1998, in press). At this stage, these points are somewhat speculative and current research is exploring this issue using Large Eddy Simulation methods applied to different combinations of bed morphology and velocity and momentum ratios.

## CONCLUSIONS

It must be said that it is very easy to criticize a method that seems a necessary element of field study, where the difficulties of data collection make it impossible to obtain instantaneous three-dimensional velocity data in an appropriate frame of spatial reference. Such data are required for many points within the flow, at frequent intervals of time, if the aim is to assess a three-dimensional flow field. Thus, the rationale behind the above observations is not to dismiss the results presented by Rhoads and Kenworthy (1998), but to suggest that it is time to move away from a theoretically unjustifiable data rotation method in river channel confluence studies. Whilst there are inevitable similarities between the flow structures in river meanders and those in river confluences, there are also important differences, to the extent that employing alternative analytical approaches may be critical to interpretation, and a necessary precursor before we can accept the argument that river channel confluences are just like back-to-back meanders. We would suggest the following conclusions.

(a) A move away from an emphasis upon secondary circulation cells and towards helical circulation is necessary, and made increasingly possible, both by using new visualization techniques for field and laboratory data, and by using numerical modelling. Visualization, perhaps aided by particle tracking, driven either by dense three-dimensional data or numerical model predictions, may allow a more effective understanding of the way in which confluent flows interact.
(b) Recent technological developments, such as acoustic Doppler velocimeters that can be used in shallow-water field environments (e.g. Lane *et al.*, 1998), do allow us to move away from the need to infer vertical velocities. However, they will continue to provide only point data, and possibly profile data, which when used to construct a flow field can provide misleading estimates of the real nature of a flow structure.
(c) Real progress rests in the synergy between field measurements and numerical modelling. The latter allows a much better spatial and temporal resolution in the information generated. However, a critical part of any modelling effort must not simply be field data for model verification, but also field data that can help identify processes for representation within numerical models. This is well illustrated by the flow field instabilities modelled using Large Eddy Simulation. Field and laboratory data helped to identify the occurrence of these in some confluence configurations (e.g. Best and Roy, 1991; Biron *et al.*, 1993, 1996), notably where there is flow separation over an avalanche face. Large Eddy Simulation has now shown that some of these periodicities can be modelled (Bradbrook *et al.*, in review, a), and with confidence in the modelling method, it becomes possible to address debates over whether or not these kinds of instability occur in all confluences through simulations of flow fields over different boundary conditions. Similarly, this model is unlikely to represent all the causes of flow instability which might occur in a natural confluence, and further field data are required to identify the nature of flow fields in other contexts to help numerical models achieve improved representation.

More general readers of *Earth Surface Processes and Landforms* may question the importance of the issue upon which this paper is based. However, there is a much more widespread philosophical conclusion that follows from the points made above. The rotation method used by Rhoads and Kenworthy has been developed for a particular type of flow structure (meandering in rivers). Any extrapolation of this analytical method to other environments has to be based upon a similarity of the basic physical principles and not a similarity of process or of form. A failure to recognize this may result in the use of methods of analysis that are inappropriate to the problem under investigation. In this case, there are basic physical *and* morphological

 

differences between meanders and confluences (Bradbrook *et al.*, in review, **b**). This does not allow the transfer of analytical approaches between the two.

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